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Publication date:
2012

Citation (APA):
Agergaard, F. A., & Ingeman-Nielsen, T. (2012). *Strength Properties of Warming Fine-Grained Permafrost*. Abstract from 10th International Conference on Permafrost, Salekhard, Russian Federation.

Strength Properties of Warming Fine-Grained Permafrost

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Background

The bearing capacity of permafrost soils are usually high compared to non-frozen soils of the same composition. The strength of these frozen soils are challenged by the projected climatic ameliorations in the Arctic, which are expected to strongly influence the distribution and thickness of permafrost during the 21st century. In Western Greenland soil temperatures are projected to increase by 2-3°C inferring Permafrost Thaw Potentials of more than 2.5 m (Daanen et al., 2011).

Fine-grained permafrost soils are especially affected by the transition from frozen to unfrozen state, primarily due to the ability to hold large amounts of ice and the influence on the soil strength and deformation properties resulting from thaw. However, also properties such as the unfrozen water content and the soil salinity play an important role (Arenson et al., 2007). With projected climate amelioration these property changes pose a challenge to the desired service life time and foundation design of new constructions.

For engineers striving to enhance and optimize the service life time of new industrial facilities and general infrastructure in permafrost areas, the projected warming poses a dilemma of whether to accommodate the subsequent change of soil properties in the foundation design or having to avoid constructing on permafrost at all. This study aims to delineate trends for the strength properties of fine-grained permafrost deposits that can be used to forecast end-of-service-lifetime-strength based on soil properties obtained from surveys performed at present day soil temperatures. The data basis is obtained from testing of natural permafrost soil core samples collected at two locations in inhabited areas of Western Greenland.

Methodology

Sample material

Permafrost soil cores have been sampled from the top of the permafrost zone in the townships of Sisimiut and Ilulissat situated at 66.9° to 69.2° northern latitude. Present soil temperatures vary from -3.5°C to 0°C. The preliminary testing classifies the soils as silty to very silty marine clays at both locations. The chloride concentration in the soil is seen to be virtually 0 mg/L indicating fully leached conditions resulting in no residual salinity. The samples from Sisimiut have a volumetric excess ice content of 18.5 % of the frozen sample volume on average while the samples from Ilulissat are virtually free of excess ice (0.1 % on average). Sample data are found in Table 1 below.

Test setup

For each location three samples have been subjected to isotropic consolidation at 100 kPa followed by undrained triaxial compression testing at a constant rate of strain (0.72%/h) maintaining a confining stress of 100 kPa to determine the shear strength at near-thawing temperatures of -3°C, -2°C and -1°C respectively. Tests were run until an axial strain of 4 %, defining the failure criterion, was obtained.

Results

Test results

The maximum shear strengths recorded of the individual triaxial tests range from 840 kPa at -1°C to more than 2 MPa at -3°C. All maximum strengths were obtained at the failure criterion after display of ductile behavior. The strength data is normalized relative to the maximum shear strength at -3°C for each location, like shown in Equation 1:

$$\tau_n = \tau_{max,T} / \tau_{max,-3} \tag{1}$$

Where $\tau_{max,T}$ is the obtained maximum shear strength and $\tau_{max,-3}$ is the maximum shear strength for test at -3°C. The resulting data points are then plotted against the temperature to obtain a trend for the development of the soil strength as a function of the soil temperature. See Figure 1. A global linear trend is expressed by the equation

$$\tau_n = -0.21 \cdot T + 0.37 \tag{2}$$

Where τ_n is the normalized shear strength relative to the shear strength at -3°C and T is the temperature in the range of tested temperatures from -3°C to -1°C.

Table 1. Classification data for the tested fine-grained permafrost samples. Location abbreviations: 'ILU' denotes Ilulissat and 'SIS' denotes Sisimiut.

Sample ID	ρ_{bulk} [g/cm^3]	ρ_{dry} [g/cm^3]	$w_{i,vol}$ [%]	w_{nat}* [%]	Test temp. [°C]
ILU 1A	2.01	1.68	0.1	19.4	-2
ILU 2A	2.03	1.70	0.1	19.4	-3
ILU 3A	2.00	1.65	0.1	19.4	-1
SIS 4B	1.50	0.82	33.5	33.5	-3
SIS 6A	1.77	1.32	8.2	29.2	-1
SIS 7B	1.69	1.18	13.9	33.3	-2

* Gravimetric water content of sample after draining of excess ice upon thawing.

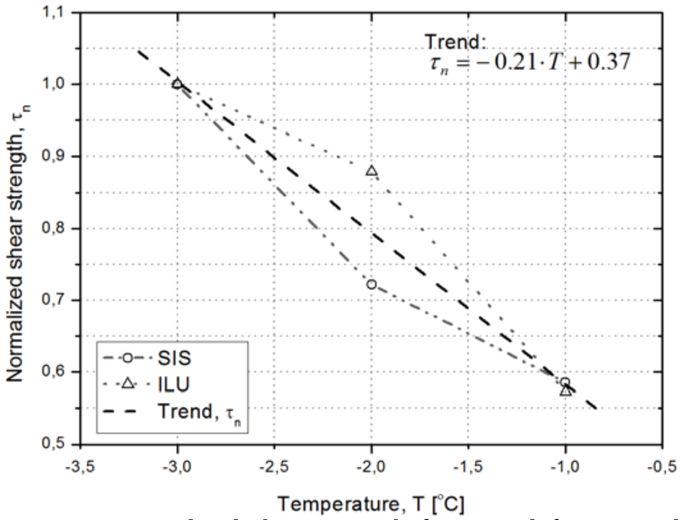

Figure 1. Normalized shear strength for natural fine-grained permafrost samples tested in triaxial compression at a confing pressure of 100 kPa.

From the shear strength failure values the soil's correspondsing undrained shear strength for use for bearing capacity evaluation based on Terzaghi's bearing capacity theory can be determined as a function of the soil temperature.

Discussion

The two series of normalized shear strengths shown in Figure 1 display a common trend of approximately 20 % decrease of strength per degree temperature increase compared to the shear strength at -3°C. This is in spite of the fact that the samples from the Sisimiut area contain moderate amounts of excess ice, which generally lowers the maximum strength compared to the Ilulissat samples. The trend of decreasing strength with decreasing dry density is also demonstrated by Li et al. (2004), who present uniaxial compression strengths of remolded clay with variations of dry density, temperature and strain rate.

A slight trend of a decreasing gradient of the curve for the Ilulissat samples may be deduced while the opposite seems to be the case for the Sisimiut samples, but further experiments must be performed before any conclusions are made in this regard. However, it makes good sense that the strength of the more ice rich samples should decrease more rapidly as the temperature close in on the freezing point as the amount of unfrozen water increase and the viscosity of the ice decrease.

If the shear strength of the design soil, having a present temperature within the tested temperature range, can be determined along with the expected soil temperature at end of construction service lifetime, then, given that the latter temperature also is within the temperature range of the tests in this study, the strength decrease due to soil temperature change can be estimated based on Equation 2. A series of these curves for different soil compositions could provide an efficient design tool for new construction designs in areas of fine-grained permafrost if used in combination with an improved regional climate model capable of delineating the development of soil temperature at a sufficient resolution. In this way the development of soil temperatures within the service life time of the construction can be predicted and the foundations designed based on the resulting corresponding bearing capacity available.

This approach is believed to contribute to a sustainable adaption of the new building mass to the projected climate changes and generally decrease maintenance costs of new constructions built on warming fine-grained permafrost and subsequently prolong the effective service life time.

Conclusion

Based on constant rate of strain triaxial compression testing of two series of natural fine-grained permafrost samples at near-thawing temperatures it is demonstrated, that a relation exists connecting the temperature and the normalized shear strength across variations in sample excess ice content. In the tested range of temperatures from -3°C to -1°C, the shear strength decrease approximately 20 % per degree temperature increase, relative to the shear strength at -3°C.

It is proposed, that the identified relationship can support the estimation of future soil strength properties for sustainable foundation design based on projected soil temperatures based on relevant climate models.

Acknowledgements

The authors would like to thank Professor Guy Doré and Researcher Jean-Pascal Bilodeau of Laval University, Quebec, Canada for kindly making available the testing facilities and invaluable technical support for the tests pertaining to this abstract respectively. We also want to acknowledge the financial support of the Idella Foundation.

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